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PLAYING WITH NETWORKS: HOW ECONOMISTS EXPLAIN

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ABSTRACT. Network theory is applied across the sciences to study phenomena as diverse as the spread of SARS, the topology of the cell, the structure of the Internet and job search behaviour. Underlying the study of networks is graph theory. Whether the graph represents a network of neurons, cells, friends or firms, it displays features that exclusively depend on the mathematical properties of the graph itself. However, the way in which graph theory is implemented to the modelling of networks differs significantly across scientific fields. This article compares the economics variant of network theory with those of other fields. It shows how the methodology employed by economists to model networks is shaped by two explanatory desiderata: that the explanandum phenomenon is based on micro-economic foundations and that the explanation is general.

1 Introduction

Network science is a recent and far-reaching research area that involves, among others, physicists, mathematicians, biologists, chemists, sociologists, epidemiologists and economists who study networks in various different domains. Ambitious claims have sometimes been made about the potential of network science to unify a wide range of natural and social phenomena and thereby the disciplines studying those phenomena. For example, well-known physicist and network scientist Albert-László Barabási (2009: 412) remarks that,

> … probably the most surprising discovery of modern network theory is the universality of the network topology: Many real networks, from the cell to the Internet … converge to similar architectures. It is this universality that allowed researchers from different disciplines to embrace network theory as a common paradigm.

The interdisciplinary literature on networks, however, remains quite fragmented and exhibits significant variation in the way in which network theory is implemented within and between different fields. Network theorists themselves are aware of the differences and tend to interpret them as being due to variations in their respective characteristic explanatory styles, rather than the result of specific subject matter. For instance, reflecting on the ways in which physical and social scientists study networks, Borgatti et al. (2009) observe that from the perspective of either side, the other's approach appears descriptive rather than explanatory.

> A curious thing about relations among physical and social scientists who study networks is that each camp tends to see the other as merely descriptive. To a physical scientist, network research in the social sciences is descriptive because measures of network properties are often taken at face value and not compared to expected values generated by a theoretical model such as Erdos-Renyi random graphs. For their part, social scientists have reacted to this practice with considerable bemusement. To them, baseline models like simple random graphs seem naive in the extreme. (Borgatti et al. 2009: 895.)

Economists frame the difference between the modelling approach of physicists and their own approach as being a difference between "mechanical" models and models that "explain why", respectively:

> While these models can yield small-world characteristics, they are "mechanical" models, where a particular process of link formation (or reformation) is specified, but there is not much explanation about why networks might form in accordance with such processes. (Jackson and Rogers 2005: 618.)

More generally, commenting on the distinctiveness of the economics approach, Matthew O. Jackson writes:

> Their [viz. economists'] interest tends to go beyond describing what is, and often tries to explain why things are the way they are. This may also seem to be an obvious point, but differences in researchers' perspectives on this issue is often a basic source of misunderstanding and miscommunication. (Jackson 2007: 21-22.)

This paper investigates the extent to which the distinctiveness of the economics modelling of networks is influenced by field-specific ideas of explanation. The increasing degree of interdisciplinary interaction between economics and the other sciences makes reflections on the characteristic explanatory style of economics particularly timely. Although philosophers of economics largely agree that the traditional interpretation of economics as subscribing to a covering law model of explanation is inadequate, as yet there is no convergence on an alternative account of explanation in economics.[1]

My strategy is to extract economists' standards of explanation in the context of a case study drawn from the study of networks. I will show that the modelling methodology employed in the economic theory of network formation is shaped by explanatory standards that also play a significant role in a larger portion of mainstream economics. These standards are that the explanandum phenomenon is based on micro-economic foundations, that the explanation is derived from unified theory and that the explanation is generally applicable. I evaluate such standards in light of a theory of explanation to separate those that reflect legitimate explanatory virtues from those that do not.

Along the way I point at a more general feature of this case study. The comparison of different models that share a common tool, namely graph theory,[2] and are intended to apply to the same target broadly understood, namely social networks, makes it possible to observe the ways in which the modelling tool is implemented in different sciences. Such implementations are guided by field-specific standards about explanation as much as (or more than) by the specific subject matter to which the models are intended to be applied. This observation is relevant for understanding interdisciplinary exchanges of modelling tools, which increasingly characterize the relationship between the natural and the social sciences and the degree and kind of interdisciplinary unity they promote.

The paper is organized as follows: Section 2 presents the main ideas about explanation that inform the subsequent discussion; Section 3 introduces network science and compares the economics approach to network formation to approaches originating in two other fields, physics/applied mathematics and analytical sociology; Section 4 examines the explanatory contribution of economics to network formation from the point of view of economists and identifies their characteristic explanatory standards. Sections 5 and 6 evaluate economists' commitments in light of a Woodward-inspired theory of explanation. Section 7 briefly comments on the general lesson suggested by the case study concerning interdisciplinary exchanges of modelling tools. Section 8 concludes.

2 Explanatory power in the sciences

This section outlines the basic machinery that informs my discussion of the way in which economists' commitments about explanation influence the implementation of network theory in economics. The philosophical machinery rests on three related insights. First, fields differ in the criteria they adopt to judge explanatory power (Miller 1987). Second, these differences are the result of norms or conventions that help to define a field's identity at particular times. Third, explanatory power has multiple dimensions.

Scientific fields differ both in regard to their modelling practices and also in regard to the criteria they adopt to evaluate the explanatory power of their models. Although this variation can be partly accounted for by their respective subject matters, part of it has to do with disciplinary conventions and traditions (Miller 1987). Scientific fields also differ in terms of the variety of explanatory styles they embody: some fields include a wide

[1] The best-known comprehensive discussion of explanation in economics is in Blaug (1992), from which I have borrowed part of this paper's title. Other important contributions include Hausman (1992), Little (1991) Kincaid (2012), Reiss (2008). The views in Hausman (2009) and Mäki (2009) are largely consistent and partly inspired the view I propose here.

[2] Following common usage, I use network theory and graph theory interchangeably, even if network theory refers to the application of the mathematical theory of graphs to the study of networks.

array of styles, each accompanied by its own standards (e.g. sociology); others, like economics, are mainly dominated by one explanatory style. Disciplinary norms regarding explanations contribute to the definition of a discipline's identity at any given time, so naturally they are intertwined with a field's prevailing modelling methodologies. The domain of phenomena that falls within a field's scope explains such norms and conventions, but not exhaustively. In some instances these norms come to define a field's disciplinary identity and take a life of their own, as it were (Woody 2003). They come to indicate how to go about explaining and modelling phenomena in a way that is independent of the requirements set by the particular phenomena under investigation.

I call *field-specific explanatory standards* those norms about explanation prevalent in a field of inquiry that have come to define a field's identity and hence have become independent from the subject matter for which they were developed in the first place. Such standards are different from idiosyncratic individual preferences because the former are shared by practitioners of the field and display a certain normative force. But they are also different from objective dimensions of explanatory power or explanatory virtues. Unlike explanatory virtues that track actual explanatory power and are derived from a theory of explanation, explanatory standards originate from their successful application in a specific field and may or may not correspond to explanatory virtues. Other things being equal, however, we would like many of those scientific standards to be accommodated within our theories of scientific explanation.

Philosophical theories of scientific explanation generally address the question of what it is that makes something an explanation. A related question, which has received relatively less attention, is what makes one explanation better or more powerful than another. One reason for this neglect is that, in most theories of explanation, once what makes something an explanation is fixed, the way in which explanatory power increases is also fixed. Even though the variations in the criteria the sciences adopt to judge the explanatory power of their models may be due to scientists' mistaken intuitions about explanation, it makes sense to explore the possibility that such criteria actually reflect different ways in which explanatory power increases.

There are at least two options for making sense of these variations. One option is to endorse pluralism about explanation and to evaluate which of these different criteria reflect the intuitions of alternative theories of explanation, the route taken by some explanatory pluralists (e.g. de Regt and Dieks 2005; van Buowel and Weber 2011). The second option is to adopt a theory of explanation that makes sense of and unifies such virtues and underlying intuitions. Among the philosophical theories of explanation currently on offer, James Woodward's account not only has currency among both philosophers and scientists, but, more importantly, is able to accommodate many of the scientists' intuitions about explanation (Woodward 2003, Ylikoski and Kuorikoski 2010). For these reasons I employ a Woodward-inspired account of explanation to assess economists' standards. In principle, an alternative theory of explanation could be adopted, insofar as it allows the existence of multiple dimensions of explanatory power. I have no independent grounds for arguing in favour of Woodward's theory except those already given by Woodward himself (2003) and his numerous supporters; I will not repeat these grounds. Many of the points I make, however, can be retained from the perspective of explanatory pluralism

Woodward's account takes explanations to exhibit (objective) patterns of counterfactual dependence between the factors cited in the explanans and the explanandum. Explanations describe how changes in the explanans bring about changes in the explanandum. In this sense explanations locate the explanandum within a range of possible alternative outcomes. Explanatory information can therefore be used to answer what-if-things-had-been-different questions (henceforth, what-if questions) and explanatory power is a function of the number and range of what-if questions the explanatory information can be used to address (Woodward 2003). This notion of explanatory power is compatible with multiple dimensions of explanatory power (cf. Hitchcock and Woodward 2003; Ylikoski and Kuorikoski 2010; Woodward 2003, 2008). The plurality of dimensions emerges from two sets of reasons. First, the range and number of what-if questions can be increased in several ways. For example, Woodward (2008) notes that causal explanations are subjected to at least two partly conflicting desiderata: that the explanation captures more of the ways in which a given cause is relevant to its effect and that the relationship between the cause and the effect is stable (more precisely, invariant) under interventions. Based on Woodward's ideas on explanation, Ylikoski and Kuorikoski (2010) also distinguish between five dimensions of explanatory goodness, which are shown to constitute more or less direct ways of increasing the number and range of what-if questions the explanatory information can be used to address.

The second source of the multidimensionality of explanatory power is identified by keeping the range and number of what-if questions fixed and focusing on the kinds of causal information explanatorily relevant in particular contexts. What makes causal information relevant in particular explanatory contexts is a function of the way in which the explanandum is described. In other words, the level of precision, abstraction and aggregation at which the explanandum is described and whether it is a single occurrence or a broad pattern determine the kind of causal information that is explanatorily (more or less) relevant. The idea is that explanations or, more precisely, explanatory strategies can be compared in terms of their goodness, depending on whether the level of specificity or generality, abstraction and concreteness, and so on at which the explanans is described is appropriate for the explanandum, that is, if it includes those and only those details that make a difference (see Woodward 2008).

Some of the dimensions of explanatory power trade off against each other, but even when they do not, actual scientific explanations may fare well when judged on one dimension while faring poorly on others. Therefore, distinct explanations and explanatory strategies can be assessed by how they perform in a number of dimensions. Note that the task of evaluating how a given explanatory strategy fares according to certain dimensions of explanatory powers is different from that of assessing which among a number of competing explanations is the best explanation of the phenomenon. The latter task requires that not only the explanations are of the same phenomenon (which is rare especially in interdisciplinary settings) and that evidence exists by which we can judge their empirical performance (which often is not available for every model). In order to keep the two tasks separate, I will assume that the models afford equally correct explanations. In Sections 5 and 6 I will use the concept of explanatory virtue to evaluate the commitments about explanation that characterise the economics variant of network theory. But first, I will examine economists' standards of explanation as they emerge from this case.

3 Models of network formation

The origins of network theory can be traced back to the theory of graphs. The graph is the mathematical object at the core of graph theory. A graph is a collection of nodes connected via a discrete set of edges. Erdös and Rényi's (1959) random networks model paved the way for modern mathematical network theory (Freeman 2004). In sociology Cartwright and Harary (1956) provided one of the first applications of graph theory to group behaviour, and since then, *social network analysis* has developed as a distinctive paradigm of research in sociology (for a historical overview, see Freeman 2004). Recently, research on networks has dramatically changed, owing to technical advances (Scott 2000) and to the increasing interest it has received in a variety of scientific fields: in the past decade, the number of articles on 'social networks' in the Web of Science has nearly tripled (Borgatti et al. 2009: 892). An extensive body of empirical work shows that the same structural properties are displayed in biological, economic, social and information networks. These findings have been taken to suggest that networks have important structural properties that can be systematically observed regardless of the phenomenon under study (Barabási 2002), and this has partly helped to spur the popularity of network science.

On the theoretical side, recent interdisciplinary work on networks generally addresses one of two kinds of questions. One concerns the formation of networks, where networks are the explananda. Examples are the following: Why and how do networks with certain properties form? Which processes can generate observed network structures? By contrast, the other kind of question concerns network influence in which networks play the role of explanantia. These models address such questions as how a person's network of relations influences her behaviour, how different structures affect individual outcomes or aggregate patterns. In order to keep the following discussion focused, I will consider only *theoretical* models of the *formation of social and economic networks*. In particular, I will contrast the economics approach to network formation with models drawn from physics/applied mathematics and analytical sociology.

Before proceeding to the comparison, a number of caveats are in order. First, the focus on models of network formation leaves open the possibility that a similar analysis in the context of models of network influence would produce different results. Since the economics approach to networks as outlined below is typically understood to characterise both kinds of models, dissimilarities between the two cases are unlikely to be significant. But even if this was not the case, my observations regarding the role of explanatory standards in the modelling of network formation and their implications regarding interdisciplinary exchanges would not be affected. Second, the illustrations from physics and sociology offer foils against which to work out the features of the economics approach; these are not intended to be representative of their respective fields. Second, I am not concerned with whether the models succeed in picking out correct causal relationships or mechanisms. Consequently, throughout the article, I assume that the models yield potential explanations that can be compared with respect to whether, and to what degree, a given explanatory virtue is displayed. Third, I will concentrate on the *formal* characteristics of these explanations qua explanations rather than on their substance.

3.1. Economics

The contemporary study of networks in economics has been set off by what is known as the *connections model* (Jackson and Wolinsky 1996), which combines network theory and game theory. The model assumes that although forming a link with another individual requires exerting effort, forming a link is valuable because it allows access to the benefits available to that individual via the link formed. Both direct and indirect connections are assumed to confer benefits to the agents, but only direct connections incur costs. Agents then form links by considering their costs and benefits. The networks that result are graphs that are stable in terms of equilibrium. The relevant notion of equilibrium is that of pairwise stability: A network is pairwise stable when (i) no agent has the incentive to sever any of the existing links, and (ii) no pair of agents has the incentive to create a non-existing link (which is meant to capture the idea of mutual consent). Depending on the costs and benefits, different network architectures are shown to be stable and/or efficient (e.g. in the model, the star, which is a graph in which all the nodes are connected to a central node, is efficient but not stable for all values). The *connections model* has thereafter been refined, modified and extended to obtain a wider range of structures, to apply to a variety of settings and also to deal with questions of network influence (Goyal 2007, Jackson 2008).

In general the microeconomics approach to networks applies game-theoretical tools and network theory to situations in which agents' decisions concern the formation or severing of links with other agents. It assumes that networks result from the strategic actions of individuals, who trade off the costs and the potential rewards of connecting with others. The strategic aspect of the interaction refers to the fact that an agent's utility function depends on the activities undertaken by the agents with whom she is linked. The generic approach to model network formation comprises the following elements (Jackson 2005: 17): Agents derive utility from the network and, hence, corresponding to any network that arises there is an overall societal welfare; links are formed at the discretion of the agents; forming a link with another individual requires exerting effort, but allows access to the benefits available to the other individual; the resulting networks can be predicted through notions of equilibrium. Alternative games of network formation specify sets of players, the types of link-formation actions that each player has at her disposal and the payoffs that arise from the nodes' linking decisions (Goyal 2007: 144). This basic machinery is applied to explain how and why networks with certain properties are likely to emerge. Economists admit, however, that the equilibrium networks that typically arise in their models display very simple structures that are rarely found in reality (Jackson 2007).

3.2. Physics/Applied mathematics

In the fields of physics and applied mathematics, the first contributions to the study of network formation were made by Rapoport (1957) and Erdös and Rényi (1959, 1960), who developed the *random networks model*. This is a dynamic model in which links across nodes form randomly and with some positive probability. For graphs of large size, that is, when the number of nodes tends to infinity, interesting properties of random networks can be identified (e.g. as nodes receive links randomly, the degree distribution of a large random graph is uniform across the nodes.)[3] However, random network models fail to produce networks that exhibit the properties that have been found to characterise many real-world networks. Watts and Strogatz's (1998) *small world model* demonstrates that generic properties exhibited by many real-world networks can be reproduced by combining randomness and clustering. This simulation-based model shows that by starting from a regular lattice that is highly clustered on a local level,[4] a relatively small amount of random rewiring of links suffices to yield networks that exhibit the following features: the links are locally highly clustered and the distance between any two nodes selected at random is relatively short.[5]

When both of these properties are simultaneously present, we speak of the small-world effect, a reference to the popular small-world phenomenon (Milgram 1967, Travers and Milgram 1969). The small-world effect is meant to capture the empirical observation that most pairs of nodes in most real-world networks seem to be connected by a short path (Newman 2003: 1). The neural network of C. Elegans, the power grid of the western United States, and the collaboration network of Hollywood actors are all shown to have the features of small-world networks (Watts and Strogatz 1998). Watts and Strogatz's model has generated massive interest within the physics/applied mathematics community. As Duncan Watts (2004: 246-247) observes, what probably most accounts for the popularity of the small world model is the "identification of a universal class of networks; that is, a family of networks that share certain aggregate properties [...] regardless of many of their individual details."

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[3] The degree distribution of a network describes how links are distributed across nodes.

[4] The level of clustering of a network measures the frequency with which relations among nodes are transitive. Transitivity indicates the extent to which if node A is linked to node B and B is linked to C, then A is linked to C. A graph is highly clustered when there are many transitivity relations among its nodes.

[5] Distance refers to the length (the number of steps) of the shortest path between two nodes.

Soon after the publication of Watts and Strogatz's model, Barabási and Albert (1999) identified a property allegedly common to real-world networks as diverse as the World Wide Web and patterns of scientific citations, which cannot be obtained in Watts and Strogatz's model. Barabási and Albert showed that independently of the system and the identity of its components, large networks exhibit a *scale-free property*, meaning that the probability that a node in a network interacts with other nodes follows a power law.[6] This property is meant to capture the empirical observation that in many real-world networks, the majority of nodes have only a few links, but a small number of nodes have a much higher number of links. Barabási and Albert (1999) succeeded in replicating the scale-free property by modelling the process of growth and preferential attachment in which, as the network grows, new nodes are more likely to form links with nodes that already have a high number of links.

Emphasising the system-independence of these properties and their underlying causes, Barabási and Albert (1999: 509) wrote:

> A model based on these two ingredients reproduces the observed stationary scale-free distributions, which indicates that the development of large networks is governed by robust self-organizing phenomena that go beyond the particulars of individual systems.

More recently, Barabási (2009: 412) added:

> [T]he main purpose of the 1999 *Science* paper was to report this unexpected similarity [scale invariant state] between networks of quite different nature and to show that two mechanisms, growth and preferential attachment, are the underlying causes.

For these theorists, modelling generic processes capable of reproducing empirical properties shared by networks of different kinds is a remarkable achievement, one connected with explanation. For instance, M.E.J. Newman (2010: 486) writes:

> But models of this kind [viz. those in which the network parameters are fixed in advance] offer no explanation of *why* the network should have a power-law degree distribution in the first place. In this chapter we describe models of a different kind that offer such an explanation. The models […] are *generative network models*. That is, they model the mechanisms by which networks are created. The idea […] is to explore hypothesized mechanisms to see what structures they produce. If the structures are similar to those of networks we observe in the real world, it suggests—though does not prove—that similar generative mechanisms may be at work in the real networks (emphasis in the original).

This quotation testifies to the observation that the physics models such as those just discussed are regarded as explanatory.

3.3. Analytical Sociology

In sociology the study of networks has a long history. Traditionally, social network analysis has been mostly concerned with questions of network influence. In recent years, however, questions about network formation have also become an important concern, partly as a result of the recent movement of analytical sociology. As its proponents see it, this movement promotes a particular approach to the explanation of social phenomena. As they put it, analytical sociology "explains by detailing mechanisms through which social facts are brought about, and these mechanisms invariably refer to individuals' actions and the relations that link actors to one

[6] That is, $\mathbf{P(k) \sim k^{-\gamma}}$ where P(k) is the fraction of nodes that have k connections to other nodes. Power laws have the property of scale-invariance.

another" (Hedström and Bearman 2009: 4). To illustrate how analytical sociologists address questions of network formation, consider the well-known study of the structure of an adolescent romantic and sexual network in an American high school by Bearman, Moody and Stovel (2004).

Bearman and colleagues obtained the structure of this romantic and sexual network from the Add Health database; what they discovered is that the resulting network displays the structure of a spanning tree. This means that the network does not have a core. A core is formed when cycles are common. The shortest cycle in this kind of network has a length of four, which would occur when an individual, *x*, forms a partnership with the former partner of the current partner of *x*'s former partner. That the network has the structure of a spanning tree means that such cycles do not actually occur. To account for this structure, Bearman et al. (2004) postulated alternative micro-level mechanisms, that is, micro-preferences that govern the choice of partners. For each mechanism, they then simulated the network structure that would emerge. The first two possibilities, that the spanning tree structure arises from a random process and from mating preferences, did not suffice to generate the observed network architecture. They then showed that the network's structure results from the existence of a social norm that proscribes students from dating the former partner of their current partner's former partner. The students were unaware of this norm, but the authors speculate that the norm may derive from the loss of status students usually associate with these kinds of relationships.

The explanatory strategy followed by Bearman and colleagues began with the identification of a clearly-delineated social-level explanandum: why does this particular network exhibit a spanning-tree structure? Second, they hypothesise different micro-level mechanisms that could generate this outcome. These hypotheses are then translated into computational models, which are simulated to derive the social-level outcome to which each model gives rise. Finally, the outcome of each model is compared to the outcome actually observed (Hedström and Bearman 2009: 16; see also Epstein 2006 and Marchionni 2013). The mechanism that produces an outcome matching the observed one is taken to possibly explain it.

4 The idea of a good explanation in economics

The high standing enjoyed by some of the fields involved in network science (notably physics) has prompted economists to make explicit their contribution to the study of networks by comparing and in some cases criticising alternative approaches. This section reviews some of the commentaries and, from those, extracts economists' ideas about explanation. Although the interest of economists in network theory is relatively recent and represents a departure from some standard assumptions of economic theory (namely by explicitly modelling the social relations among agents), what transpires from the following analysis reflects what many will recognize as economists' long-standing methodological commitments (see for instance Hausman 1992, Mäki 2009, Kincaid 1996, 2012). Presumably this is why they are deployed to highlight the distinctiveness of the economic approach to networks.

Economist Sanjeev Goyal (2007) claims that the distinctiveness of the economics approach to networks lies in the different methodology used: "These differences can be traced to a substantive methodological premise in economics: social and economic phenomena *must be explained* in terms of the choices made by rational agents" (Ibid.: 7; my emphasis). Matthew O. Jackson (2007) points out that physicists' models of network formation leave unexplained why social networks exhibit the features they do. Physicists' models address

> […] the how, but not the why. Insights from the economic perspective complement Watts and Strogatz' approach and instead of offering a process that will exhibit such features, offer an explanation of why people would tend to form networks with such features (Jackson 2007: 32).

Similarly, de Martí and Zenou (2011: 346) point out that in Watts and Strogatz (1999), "the 'social structure' is represented by a uniform one-dimensional lattice. This is an assumption and we do not know why and under which conditions this network structure prevails." De Martí and Zenou (2011: 346) also observe that Barabási and Albert (1999) "never justify why agents will behave according to the preferential attachment rule. On the contrary, by focusing on the optimal behaviour of agents in making links, we can understand why certain network structures emerge." Finally, Jackson and Rogers (2005) claim that physicists' models are "mechanical models" in which "a particular process of link formation […] is specified, but there is not much explanation about why networks might form in accordance with such processes." Consequently, "new processes can be needed everytime some difference in network structure is observed empirically." (Jackson, 2007: 18; see also de Martí and Zenou 2011: 346).

Economists have also sought to distinguish their approach to modelling networks from that of sociologists. According to Podolny and Rauch (2007: 4), whereas economists "look to the characteristics of actors to understand the formation and dissolution of ties", sociologists typically "look to the pre-existing patterns of ties as the determinant of subsequent tie formation." Sociologists would point to chance and path dependency to explain why pre-existing patterns are the way they are, but Podolny and Rauch go on to note that for economists, "these explanations do not constitute a theory." As we have just seen, economists see as a shortcoming of the physicists' models that they have to invoke different processes for different explananda. This presupposes that economists see the ability of their models to use the same behavioural rules for different settings as a virtue of their approach. So although economists have not commented specifically on the model of Bearman and colleagues, it is safe to assume that they would also regard an explanatory micro-mechanism based on the no-four-cycle rule as *ad hoc* for two related reasons: first, it is specifically tailored to obtaining the features of the specific network under study and second, it does not derive from any general theory of individual behaviour. For economists, it is better (in the sense I will specify below) to postulate the same kind of agents' behaviour to derive the properties of networks across different situations (see also Hausman 1992, Mäki 2009).

A related feature that sets the economics approach to network formation apart from the modelling approach exemplified by Bearman et al. concerns the primacy of the explanans vis-à-vis the explanandum. In line with the tenets of analytical sociology, Bearman et al. start from a "clearly specified social fact" (Hedström and Bearman 2009: 16) obtained from the empirical study of a particular social system, in this case, the fact that the sexual network mentioned above displayed a tree-like structure, and investigate what micro-level mechanisms could account for it. By contrast economists even when they build their models for the explanation of *stylised facts* obtained from empirical studies,[7] the explanatory mechanism is obtained from modifications of the template. Consequently, the modelling and explanatory practices of sociologists and economists not only differ in terms of the kinds of behaviour they customarily assume for agents (say, strategic interaction versus influence of social norms), but they also appear to entertain divergent conceptions of what makes certain ways of constructing explanations better than others.

[7] In economics the term '*stylised fact*' is typically used to refer to a stylised description of a pattern obtained from the analysis of a particular body of data. The following empirical patterns obtained from the Add Health database and pertaining to friendship networks are examples of stylised facts: "larger groups tend to form more same-type ties and fewer other-type ties than small groups;" "larger groups tend to form ties per capita;" "all groups are biased towards same-type relative to demographics […]" (Currarini et al. 2009: 1003).

To sum up, economists hold that their approach can remedy two shortcomings in the current modelling of network formation: the absence of microfoundations and the lack of generality. The absence of microfoundations captures the idea that the generative models of physicists are less explanatory insofar as the social structure is assumed rather than derived and because they do not include accounts of why nodes form links in the way they do. The lack of generality captures the intuition that the models of both physicists and sociologists are explanatorily defective because they need to postulate *ad hoc* processes/mechanisms to account for different properties and that apply across systems or situations. In positive terms, these ideas can be summarised in three requirements that together define economists' standards of explanation:

a) *The mechanistic requirement*: the derivation of social structure in terms of why nodes form links the way they do.
b) *The unification requirement*: the explanatory mechanism is to be derived from a unifying theory.
c) *The scope requirement*: the same mechanism should be shown to apply across systems or situations.

In the next two sections I will evaluate these requirements in light of the theory of explanation described above. I will conclude that the unification requirement does not correspond to an explanatory virtue, but that the mechanistic and the scope requirements do. Note that it is possible to accept my analysis of how economists' explanatory standards influence their modelling approach to networks, but disagree with my assessment of those standards in terms of explanatory virtues. Moreover, regardless of whether a requirement corresponds to an explanatory virtue, it may still be found to be instrumental to the attainment of other epistemic goals.

5 Mechanisms and explanatory depth

As is well known, in economics a good explanation is commonly held to be one that shows how the phenomenon to be explained results from the actions and interactions of rational agents. The kinds of mechanisms economists deem explanatory are at the micro level, where 'micro' refers to the level of individuals, households and firms. In particular, the modelling of network formation proceeds by assuming that agents form links, which are costly, in order to gain access to the benefit available to other agents. The mechanism of network formation thus describes the interaction between the link-formation actions of the agents and the associated payoffs; it is this interaction that gives rise to (equilibrium) networks with different structures. But how does the description of these mechanisms purportedly improve on the explanations of network formation put forward by physicists?

To answer this question, consider Jackson's (2007: 33) description of how the economics approach accounts for the formation of small-world networks and hence contributes to the explanation given in Watts's and Strogatz's model (1998). There are different costs and benefits associated with having links with different kinds of nodes. Links between nodes that are close, either geographically or in terms of some other characteristics, are cheap, whereas links between distant nodes are comparatively more expensive. It follows that high clustering emerges between individuals for whom the costs of forming links are low. On the other hand, distant links convey higher benefits because they allow access to distant parts of the network and hence to information that is not available from local sources. Therefore, because distant links are so costly, fewer are likely to emerge, but because they are valuable, they will not be entirely absent. The existence of distant links ensures that the diameter of the emerging network will not be too large and the distance between any two nodes will be relatively short compared to a random network. The formation of small-world networks can thus be related to changes at the level of the costs and benefits of forming links. In Section 3.2 we saw that Watts and Strogatz's (1998) demonstrated how, starting from a regular lattice, the small-world property can arise from the random rewiring of a few distant links. Watts and Strogatz's model is explanatory in that it identifies the range of conditions (the degree of randomness) under which the small-world effect emerges, but it includes virtually no information about why nodes form many links with close-by nodes and only a few links with distant nodes.

Call *explanatory depth* the dimension of explanatory power in which explanatory improvements occur by adding explanatorily relevant details about the *mechanism* that brings about, produces or constitutes the explanandum phenomenon (e.g. Craver 2007). Recall from Section 2 that in Woodward's account, explanatory power is a positive function of the range of what-if questions the explanatory information can be used to address. Adding relevant details about mechanisms constitutes an increase in explanatory power insofar as it reveals the conditions under which the dependency relations in the original explanation change or break down. This information is obtained by way of relating in a systematic way changes at the level of the components of the mechanism to changes at the level of the explanandum phenomenon (Craver 2007; Woodward 2003, 2008).

If and when correct, the economics models of network formation are deeper than the physicists' models in the sense just specified. The economics models in fact give an account of why nodes form the distant links seen in Watts and Strogatz (1998).[8] In so doing, they relate changes at the level of nodes (e.g. costs and rewards, available strategies) to changes at the level of the network (e.g. the level of clustering, the mean distance between nodes), and hence they can be used to address a wider range of what-if questions about how changes at the level of costs and rewards, strategies and so on bring about changes in the architecture of the resulting network.[9]

Analytical sociologists also have a preference for models in which network formation results from individual-level mechanisms (and often explicitly endorse a version of methodological individualism called structural individualism; Hedström and Bearman 2009). As I will discuss in more detail below, the main difference between the two approaches is that the mechanisms postulated by sociologists rest on behavioural hypotheses that are tailor-made to account for a specific situation and are not derived from a general theory of individual behaviour such as rational-choice theory.

Before moving on to discuss the explanatory contribution of the economics variant of networks vis-à-vis the sociologists' models, let me briefly mention two aspects of the mechanistic requirement as endorsed by economists that are not easily licensed by the account of explanation adopted here. These aspects are clearly expressed by Goyal's statement quoted above, that "social and economic phenomena *must* be explained in terms of the choices made by rational agents." Economists indeed generally subscribe to the view that (i) an explanation of social and economic phenomena is successful *only* when an individual-level mechanism is described and (ii) an explanation of economic phenomena is successful *only* when a mechanism involving *rational* agents is described. Philosophers of economics have extensively discussed these ideas and I will not repeat these debates (see for example Kincaid 1996). Here it is sufficient to note that it is questionable whether explanations of social and economic phenomena are only or always improved by providing details about micro-

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[8] Or why nodes are more likely to connect with nodes having many connections as in Barabási and Albert (1999). I am not aware of strategic models of network formation that provide micro-foundations to the preferential attachment process. Jackson and Rogers (2007) offer a hybrid model that derives the network from a random process and has implications for welfare.

[9] Clearly this is only so when the behaviour of nodes can be conceptualised in terms of strategic interactions. Therefore, the potential scope of application for economists' models is narrower than that for physicists' models. In addition, claiming that economics explanations are deeper does not amount to saying that they are better; they constitute improvements only on this particular dimension of explanatory power.

level mechanisms. Reductionist strategies may also fail to yield explanations with other virtues, for example, because causal dependencies at the higher level may be more stable or invariant than those at the lower level (cf. Woodward 2003; for an exposition of the view that social mechanisms need not be at the micro-level, see Kincaid 1996). Second, individual-level mechanisms need not always involve rational agents; alternative behavioural assumptions may be equally, if not more, plausible depending on the context and the purpose.[10]

6 Generality and explanatory breadth

Both economists and analytical sociologists subscribe to the idea that explanatory depth is an important dimension of explanatory power, achieved by identifying the individual-level mechanisms that bring about the social facts to be explained (e.g. Hedström and Bearman: 2009, 8-9). What then, if anything, distinguishes the economics approach from that of analytical sociology?

Economists claim that the models of sociologists (as well as the models of physicists) assume a different process, mechanism or set of behavioural rules for the explanation of different properties of networks and/or for different settings. By contrast, in economics properties exhibited by many kinds of networks and across different situations are obtained from the *same kind* of mechanisms. This idea resonates with the intuition that underlies unification theories of explanation (Kitcher 1981). Philosophers of economics have already observed economists' commitment to explanatory unification (e.g. Hausman 1992, Mäki 2009). Unificationist accounts of explanation, however, are hard to reconcile with causal accounts, and Woodward himself has explicitly argued that unifying power does not track explanatory power. Although accounts of explanatory unification involve both large scope at the level of the explananda (many kinds of networks and across different situations) and few explanatory mechanisms or principles (same kinds of mechanisms) to explain them, the scope requirement can be evaluated separately from the unification requirement. Sticking to the Woodwardian view that x is an explanation in virtue of the fact that it uncovers causal dependencies, we can ask and assess the desirability of two separate attributes of x: the explanatory mechanisms belongs to a unified theory and so they are of the same kind (the unification requirement), and the explanation explains properties of many systems or situations (the scope requirement).

First, that a given explanation belongs to a unified explanatory corpus as required by the unification requirement has little to do with explanatory power if the latter is taken to be a function of the range of what-if questions. The range of what-if questions a given explanation addresses remains unaffected by whether the explanans is derived by a unified theory or is specific to a particular explanandum. Even so, however economists' commitment to unification could be justified on other grounds. To appreciate this possibility, let us consider two principles both involving unification (Sober 2003: 206):

[U_1] That a hypothesis provides a unified explanation of a set of observations, while a competing hypothesis provides a disunified one, constitutes evidence in favour of the former hypothesis.

[U_2] If two hypotheses are true, but only one provides a unified explanation of the phenomena, then the unified explanation explains the phenomena but the disunified one does not.

Because the Woodwardian account of causal explanation only denies that the latter is the case, economists' commitment to unification could nevertheless be justifiable along the lines of principle [U_1] above. As mentioned above, my working assumption that the explanations the models afford are correct serves to focus on

[10] The claim that the economic mechanisms involve the rational choices of agents is compatible with assumptions of full rationality and of bounded rationality.

explanatory virtues, leaving aside evidential considerations. Evidential virtues do not exhaust the grounds on which a commitment to unification could be justified, but what this distinction is meant to highlight is that denying a role for unification in explanation does not imply denying any role to unification in science.

Second, it is not at all obvious why wide scope tracks explanatory power if it is disconnected from a unificationist account of explanation. In fact breadth is typically obtained by increasing the level of abstraction at which both the explanans and the explanandum are described. Hence, in order to enlarge the scope of an explanation a host of specific details have to be omitted (cf. Jones 2005). But this runs counter to the widely-held presupposition that the more detailed and complete the description of the causes that bring the explanandum phenomenon about, the better the explanation. In Woodward's account, *ceteris paribus*, the omission of causal details affects negatively the number and range of what-if questions that can be addressed.

However, the kinds of causal details that are explanatorily relevant in a given context are determined by the explanandum and the level at which it is described. Hence, the question of whether broad explanations have an explanatory added value then becomes a matter of whether there is a class of explananda that is best explained by explanations having this property. Matthew O. Jackson (2007: 22) suggests an answer:

> This interest in the "why" naturally leads to some abstraction away from the full detail of a setting, which can lead to the omission of important factors. At the same time, the tendency towards abstract modeling can help provide insights into why certain regularities might appear in social and economic networks.

Abstracting from the full details of a setting is believed to help deliver explanations of "why certain regularities appear in social and economic networks". In fact, it is precisely because of their abstract character that the same economic mechanisms can be applied easily across contexts and domains. In general, it is the success in delivering explanations for such regularities that underscores the use of general models of abstract mechanisms (in a way that is similar to physics models). When we are seeking to explain such regularities, explanations that include system-specific details obscure the fact that the regularity to be explained is brought about by what the systems have in common rather than by what is specific to each (e.g. Batterman 2002, 2009; Jackson and Pettit 1992; Sober 1999). Hence, when the behaviour displayed by different kinds of systems can be shown to result from the same kind of abstract mechanisms, system-specific details do not matter and should not be included. Call *breadth* the explanatory virtue displayed by explanations of this kind.[11] According to the theory of explanation adopted here, explanatory breadth counts as an explanatory virtue insofar as and to the extent that broad(er) explanations are uniquely suitable to address (what-if) questions about regularities and properties shared by a variety of systems.

If breadth is a positive function of the omission of details about systems and depth is a positive function of the number of details about mechanism, then how can economics models simultaneously deliver broad and deep explanations? I have used "details" in both cases, but without qualification this parlance is misleading: the causal details relevant for achieving depth are *details about the mechanism*, whereas those that matter for achieving breadth are *details specific to the system(s) to which the model is intended to be applied*. Consequently, while it is true that explanations lacking information about mechanisms are shallow, explanations that include system-specific details have a narrow scope, but this does not necessarily make them any deeper. As I argued elsewhere (Marchionni 2008), it is quite possible to give a very detailed explanation that does not include a description of the underlying mechanism. So when generic patterns of behaviour are explained by the operation of common

[11] The terms "depth" and "breadth" come from Sober (1999).

mechanisms described in an abstract manner, explanations can be broad and deep at the same time. Again assuming that the substantial assumptions on which explanation in economics is based can deliver correct explanations at least most or some of the time, the explanatory contribution of the economic models of network formation can be seen as stemming from the simultaneous pursuit of two explanatory virtues: explanatory depth, which calls for the description of the micro-level mechanisms that bring phenomena about and explanatory breadth, which requires abstracting from details specific to a system or situation.

Not all abstract mechanisms are explanatory, however. An abstract model may simply omit too much to be of explanatory use in the first place. Commenting on network science, Evelyn Fox Keller (2005) expressed two worries. First, she questioned whether Barabási and Albert's (1999) process of growth and preferential attachment leads to scale-free networks, not because it is a universal process, but because the model assumes so little and scale-free distributions are relatively easy to obtain. Similarly, it is possible that the same economic mechanisms of network formation apply widely because so little is required for them to apply. Second, she observed that, although some properties of real-world networks can be understood without attending to the details of the system, it is legitimate to ask how many actual properties of real-world systems can be so understood. It is one thing to say that the abstract modelling strategy that characterises both the physics and economics approach to networks is explanatory for a class of explananda; it is another thing to maintain that this strategy is capable of explaining much of what is empirically relevant about the formation of real-world networks. Hence, what we can learn about real-world networks from general models of abstract mechanisms that apply across the board and how much of it is relevant remain open questions.[12] It should also be borne in mind that breadth and depth can trade off with other dimensions of explanatory power such as, for example, Woodward's degree of stability. I do not investigate those other trade-offs here. The general point is that the likely consequence of a scientific field's systematic preference for explanations that fare well on some dimensions of explanatory power is that other dimensions are systematically neglected.

7 Interdisciplinary exchanges

In a recent and influential contribution Paul Humphreys (2004) takes the travelling of the same mathematical forms across disciplines, which he calls *computational templates*, as an important feature of contemporary science (see also Knuuttila and Loettgers 2011; Grüne-Yanoff 2011). Such templates can be single equations, such as the wave equation, all the way up to modelling techniques, such as agent-based models. According to Humphreys, the exchange of such templates across disciplinary boundaries leads to rethinking the organisation of the sciences; rather than being defined by their concrete subject matters, the sciences should be, and to some extent they are becoming, organised around templates.

But what is it that characterises those bits of mathematics that travel across disciplines? According to Humphreys, the ability of computational templates to travel is due in part to their flexibility and their independence from the subject matter. Yet their adaptation and their eventual adjustments to specific kinds of systems is and should be dictated by the exigencies of the subject matter. As he puts it, "the adjustment processes underlying the templates require that attention be paid to the substantive, subject-dependent

[12] The narrow focus on a restricted set of explanatory factors and the systematic preference for certain explanatory virtues could find justification in the division of cognitive labour between the sciences dealing with networks. Evaluating the plausibility of this scenario goes beyond the scope of this article.

assumptions that led to their adoption" (Humphreys 2004: 71). The concrete subject matter guides and constrains the construction of the templates in different applications.

The case of network theory draws attention to another source of modifications of such templates: the explanatory standards prevalent in a field (in at least some cases) guide the processes of modification of templates in ways that are independent from the requirements of the subject matter to which the models are intended to apply. This in turn has consequences for the reorganization of the sciences that Humphreys envisages. This case could be an exception, but even so it suggests an aspect of travelling templates that has so far gone unnoticed.

To be clear, I am not suggesting that Humphreys' is an incorrect description of what is now taking place in science. Nor do I wish to exaggerate the differences between the case I analyse and the ones Humphreys is concerned with. First, the boundaries between a field, a method and a domain of inquiry are vague so that modifications of a template derived from a field's explanatory standards or from the subject matter are hard to distinguish. For example, is the economists' mechanistic requirement a field-specific explanatory standard or is it a consequence of the interest in economic and social networks characterised by the presence of strategic interactions? Second, the phenomena themselves provide constraints on which kinds of mathematical forms will fit them and which will not. Modelling strategic interactions requires game theory, which, in turn, requires network theory to be adjusted so that it can be used in a game-theoretical framework. For both of these reasons the application of a modelling methodology cannot be fully independent from the characteristics of the subject matter.[13] Nevertheless, it is instructive to distinguish between the two sources of modification: those that derive from the requirements of the subject matter and those that are dictated by the explanatory standards prevalent in a field. Though in many cases of successful application the two sources will be indistinguishable, in other cases one or another source will play a more decisive role.

When disciplinary conventions about explanation and modelling play a larger role in dictating modifications of common templates, the tendency towards the kind of interdisciplinary organisation Humphreys identifies may not take place after all; disciplinary rather than interdisciplinary unity remains stronger. In the economics of networks explanatory standards seem to play a major role in the elaboration and adaptation of network theory in a way that goes well beyond fitting them to the specific subject matters. Hence, the affinity between, say, the economics variant of networks and standard economics appears to be stronger than that between the economics variant of networks and applications of network theory in other disciplines, even if the commonality has less to do with the subject matter than with the modelling approach characteristic of the field. If I am right that the mathematical tools are moulded so as to fit the standard modelling methods characteristic of each field, then the affinity between models of networks across disciplinary boundaries may not be as strong as it may appear. This provides another reason for downplaying the unificationist aspirations that are sometimes made on behalf of network science.

This is not to deny that various kinds of interdisciplinary exchange have also been taking place. Several models of both network influence and network formation combine ingredients from different approaches, such as economic models that employ centrality measures first developed in social network analysis (e.g. Ballester et al. 2006); work on Watts and Strogatz (1999)'s small-world topology carried out in economics and in sociology

[13] More generally, a model's format constrains its content and vice versa (see Morgan 2012). Exploring the multiple aspects of the relation between format and subject matter in a comparison between economics and physics models of networks would be worth a paper of its own.

(e.g. Jackson and Rogers 2005; Centola et al. 2005); the sharing of databases such as the Add Health across a variety of disciplines (e.g. Bearman et al. 2004 in sociology, Currarini et al. 2009 in economics). Articles and books co-authored by scientists from different fields have been published (e.g. Podolny and Rauch 2007; Acemoglou et al. 2001; Easley and Kleinberg 2010) and the journal *Network Science* has recently been launched with the aim of promoting interdisciplinary communication. It is too early, however, to predict whether such efforts will effect significant changes to network science, or instead various forms of interdisciplinary exchange will continue to coexist with the diversity of field-specific modelling practices.[14]

8 Concluding remarks

The comparison with alternative strategies of modelling network formation shows how economists' view of explanatory power accounts for the distinctiveness of their modelling approach to networks. In particular, the explanatory contribution of economics to the explanation of network formation is shown to proceed as follows: economic models aim at providing deep explanations in that by deriving networks from individual-level mechanisms, they can systematically relate changes at the level of the network to changes at the level of the individual; general models of abstract formation mechanisms aim to deliver broad explanations that can account for (thus far fairly simple) properties shared by many kinds of social and economic networks. The comparison between strategies of modelling network formation also shows that the application of network theory is influenced by the explanatory standards and modelling techniques typical of the field in a way that is partly independent of the specific subject matter. This provides a further reason to take with caution the claims to unification advanced by some proponents of network science.

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[14] Whether current claims to unification are warranted does not depend on whether network science will or will not be fragmented. Moreover, even if network science will eventually develop as an autonomous field, this in itself does not warrant claims to the unification of phenomena across disciplinary boundaries.

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